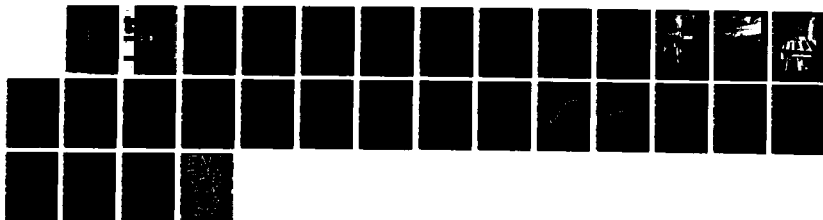AD-A194 916   DYNAMIC LOADING ON SIDEWALL MONOLITHS OF A SPILLWAY   1/1
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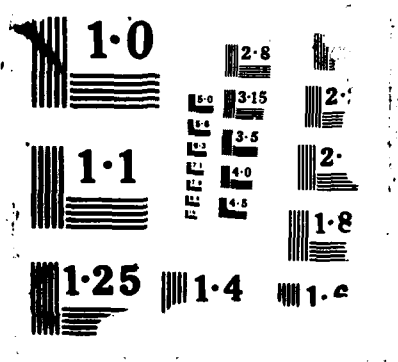   EXPERIMENT STATION VICKSBURG MS HYDRA..
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US Army Corps
of Engineers

AD-A194 916

DYNAMIC LOADING ON SIDEWALL MONOLITHS OF A SPILLWAY STILLING BASIN

Hydraulic Model Investigation

by

Bobby P. Fletcher, Peter E. Saunders

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
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LABORATORY

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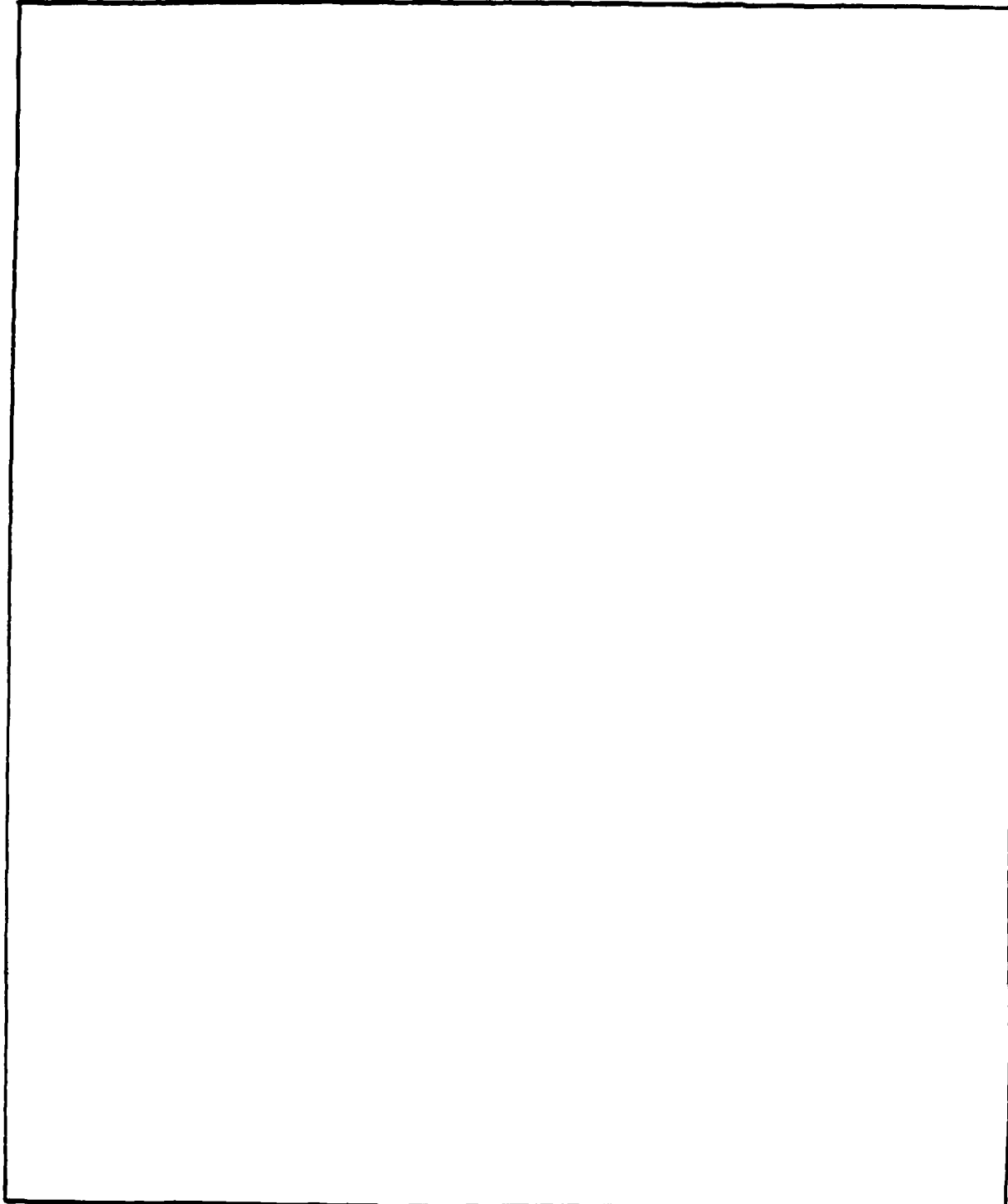US Army Corps of Engineers
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			Sequent depth

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Guidance for determining the magnitude of hydraulic forces acting on a stilling basin sidewall is presented.

A designer knowing the unit discharge, spillway height, velocity entering the stilling basin, Froude number, sequent depth, and tailwater depth can compute the average hydraulic force and maximum pulsations for any increment of sidewall length. The maximum overturning moment about the base of any portion of the sidewall can also be determined.

Appendix A presents an example problem illustrating the recommended application for estimating the magnitudes and locations of the resultant dynamic forces acting on a stilling basin sidewall.

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PREFACE

The investigation reported herein was authorized by the Office, Chief of Engineers (OCE), on 18 February 1969 as a work unit of the Locks and Dams Research and Development Program which became the current Flood Control Hydraulics Research and Development Program. The study was begun in February 1969 in the Hydraulics Laboratory (HL) of the US Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. H. B. Simmons and F. A. Herrmann, Jr., past and present Chiefs, HL, and T. E. Murphy and J. L. Grace, Jr., past and present Chiefs of the Hydraulic Structures Division. Testing and analysis were conducted by Messrs. M. B. Savage and C. B. Cox, Instrumentation Services Division; and W. A. Walker, P. E. Saunders, and B. P. Fletcher, Spillways and Channels Branch, Hydraulic Structures Division, under the supervision of Messrs. Grace and J. P. Bohan and N. R. Oswalt, past and present Chiefs of the Spillways and Channels Branch. This report was prepared by Messrs. Fletcher and Saunders, reviewed by Messrs. Grace, Laboratory Program Manager, and S. B. Powell, OCE Technical Monitor, and edited by Ms. J. W. Leach, WES Information Technology Laboratory.

COL Dwayne G. Lee, CE, is the Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
foot-kips	1.355818	metre-kilonewtons
inches	2.54	centimetres
kips per foot	14.5939	kilonewtons per metre
square feet	0.09290304	square metres

DYNAMIC LOADING ON SIDEWALL MONOLITHS OF A

SPILLWAY STILLING BASIN

Hydraulic Model Investigation

PART I: INTRODUCTION

Background

1. The turbulence of a hydraulic jump imposes pulsating forces against
a stilling basin sidewall. The magnitude, frequency, and distribution of
these dynamic loads are of interest relative to the structural design of
stilling basin sidewall monoliths. However, the lack of adequate means for
estimating the characteristics of these dynamic loads has been recognized as
well as the need for the research reported herein.

2. Past practice has consisted of designing walls to withstand the
loads resulting from the maximum anticipated differential heads due to water
and/or soil loadings, plus an additional unknown but estimated dynamic load.
Previous laboratory measurements with pressure transducers have indicated that
the pressure near the base of a wall may fluctuate from the static pressure as
much as 1.5 times the velocity head entering the basin. Although dynamic
loadings equivalent to such pressure fluctuations have been used in the design
of stilling basin sidewall monoliths, there has been concern that this prac-
tice is too conservative since it is believed that pressure fluctuations on
areas as large as sidewall monoliths are considerably less than those on small
pressure transducers.

Purpose and Scope of Study

3. This study was undertaken to provide a method for the investigation
and prediction of the magnitude, frequency, and distribution of dynamic loads
imposed on stilling basin sidewall monoliths by the turbulence in a hydraulic
jump. The approach taken consisted of measuring hydraulic forces on model
monoliths of various sizes rather than measuring point pressures. These test
results are limited to stilling basins without basin elements. However, it is
anticipated that guidance in the design of sidewalls for stilling basins with
baffles and end sill can be obtained from this report.

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PART II: MODEL AND TEST PROCEDURES

Test Facilities

4. The tests were conducted with monoliths located along the left side of a stilling basin downstream of a spillway installed in a 7-ft-wide,* 4-ft-deep, and 71-ft-long flume (Figure 1). Two 2.5-ft-long ogee spillway crests with heights H_s of 0.9 and 1.6 ft were formed of sheet metal.** Each crest had a design head H_d of 1.0 ft. The crests were surmounted by one 0.204H_d-ft-wide pier located to permit a 1.0H_d-ft-radius abutment and 3.4 ft of nonoverflow section. The spillway emptied into a stilling basin 2.5 ft wide and 9 ft long (Figure 2). The stilling basin floor was formed of plastic-coated plywood. One wall of the spillway basin was made of glass to permit observation of the hydraulic jump, and the other was formed of seven machined aluminum monoliths to permit measurement of lateral hydraulic forces (Figure 3).

5. Individual monoliths were supported in the vertical plane by a pair of double hinges (Figure 4) at the bottom to ensure freedom of movement only in a direction normal to the longitudinal center line of the hydraulic jump. Strain gages were located at the bottom and 1 in. from the top of each monolith. This arrangement permitted determination of the magnitude and frequency of loads normal to the sidewall and the moment arm of these loads.

6. The strain gages received a DC voltage excitation, producing a record which could be reviewed on an oscillograph and stored on analog magnetic tape (Figure 5). These records were later reduced on an analog-to-digital converter to a form which could be more readily analyzed.

Test Procedures

7. A series of 125 tests were conducted with the monoliths, an ogee-shaped spillway, and a stilling basin that contained no baffle blocks or end sill. The variables investigated included monolith height and width, entering

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.
** For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix B).

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Figure 1. Upstream view, spillway crests and seven sidewall monoliths

Figure 2. Downstream view, spillway crests and seven sidewall monoliths
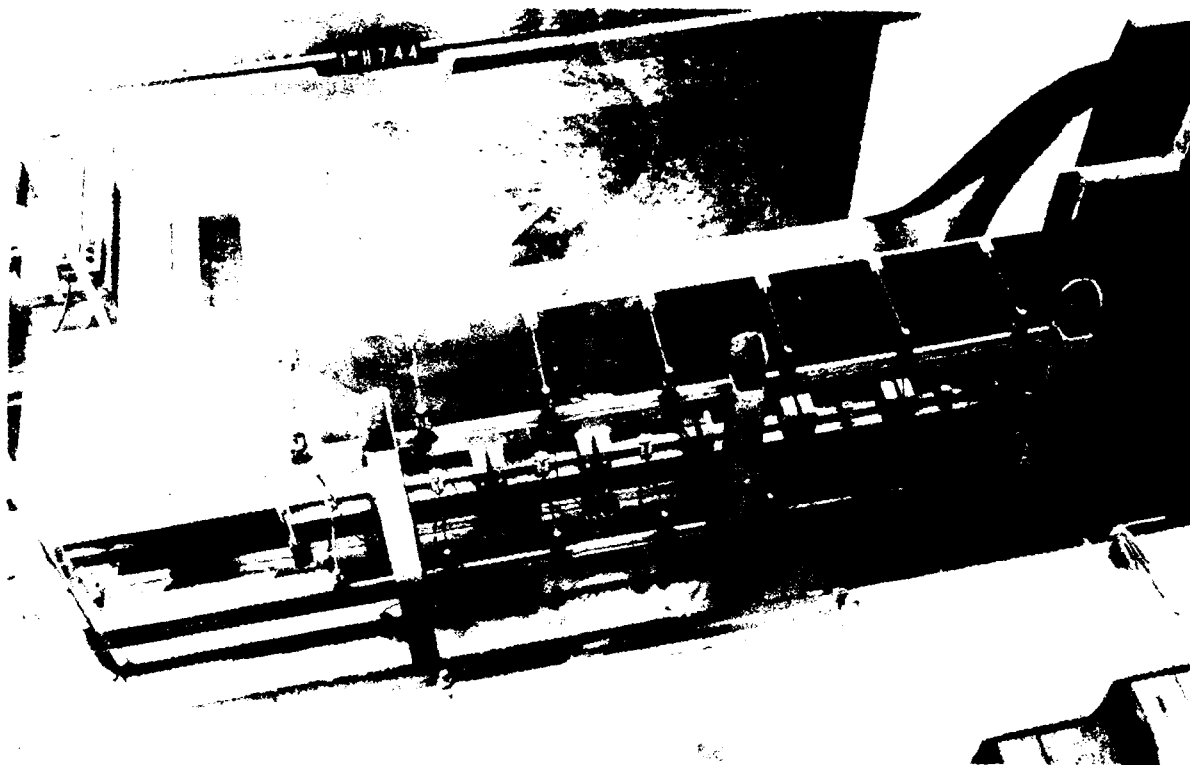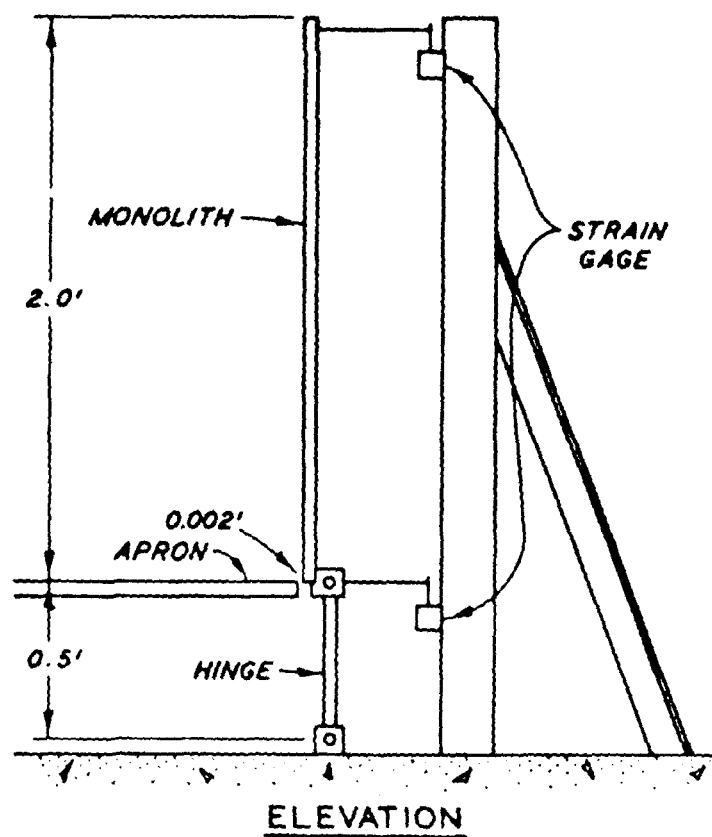
Figure 3. Back view, seven sidewall monoliths
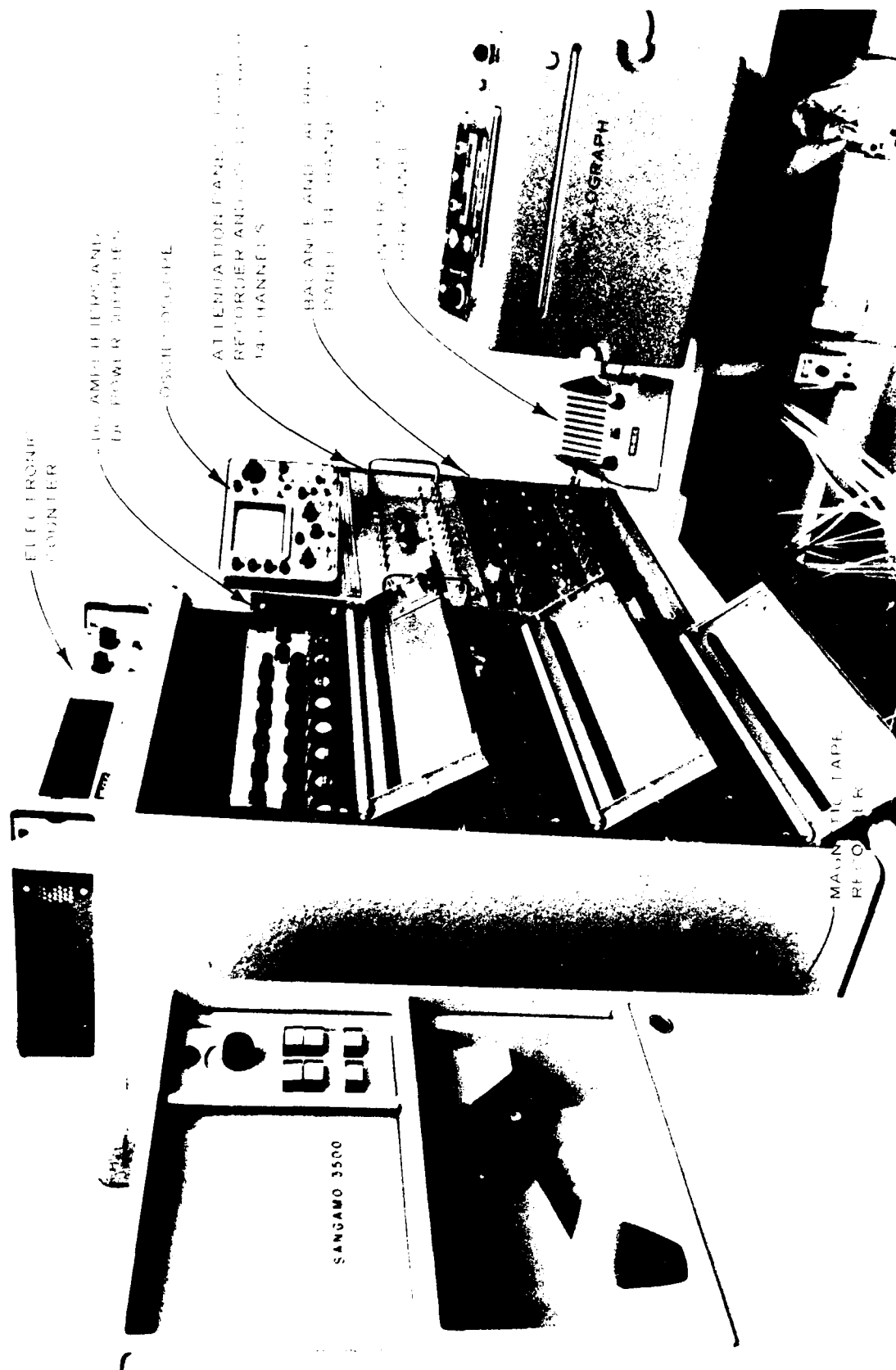

Figure 4. Typical monolith
section

MONOLITH

STRAIN GAGE

2.0'

0.002'

APRON

0.5'

HINGE

ELEVATION

Figure 5. Instrumentation

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Froude number of flow, discharge, tailwater elevation, spillway height, and sidewall length.

8. Seven different discharges were used in conjunction with various spillway heights and monolith dimensions. The monolith widths investigated ranged from 0.5 to 1.25 ft in increments of 0.25 ft. The monolith heights were varied from 1.0 to 2.5 ft in increments of 0.5 ft. Tailwater depths downstream of the hydraulic jump were varied for each combination of discharge and monolith dimensions. Tests were also conducted with a spillway height of 0.9 ft to determine the effect of spillway height on the sidewall forces.

9. A series of tests were conducted to determine if the natural frequency or dampening of the system would influence measurement of the forces. The results of these tests revealed that the frequency of the exiting force in the hydraulic jump did not exceed about 5 Hz, and the natural frequency of the model monoliths and linkage (100 Hz) was too high to influence the force measurements through resonance effects. Several tests were conducted with and without water on the back of the sidewall. There was no discernible dampening of the forces due to the mechanical system or the hydrostatic load on the back of the monolith. Since it was desired to measure only the forces generated from the hydraulic jump, the force due to the water on the back of the wall was subtracted from the measured force. It is anticipated that no damage to a prototype wall would be caused by the wall being in resonance with the periodic forces in a hydraulic jump since the measured frequency of the periodic pulsations in the experimental facility (5 Hz) divided by the square root of the appropriate scale required for similitude is much lower than the computed natural frequency of a typical prototype wall. Also, model tests indicated that the magnitude of the random pulsations exceeded the magnitude of the periodic pulsations by a factor of 20; therefore, only test results pertaining to the magnitude of the random pulsations will be presented in this report.

PART III: TESTS AND RESULTS

Dynamic Loads Within a Stilling Basin

10. The usual analysis for prediction of the average dynamic force exerted on the sidewall is based on the assumption that it is probably equivalent to the static force due to the head differential between the water depth in the basin on one side of the monolith and tailwater depth on the other. However, very little information is available on the surface profile through a hydraulic jump, the extent of high-velocity jet flow, and the roller portions of the hydraulic jump that can be readily used for design purposes. This is attributed to the difficulty of physically measuring the flow characteristics and the water surface through a jump and the lack of mathematical descriptions of the jump characteristics and profile.

11. The results of the tests and data analyses indicate that the average minimum unit force on sidewall monolith R_m exerted on the sidewalls occurs approximately at a point located 15 percent of the jump length downstream from the toe of the jump and is a function of the momentum of flow $\rho V_1 q$ and the Froude number of flow F_1 entering the stilling basin. A plot of the results of data analyses that shows the relation between the ratio of the average minimum unit force R_m to the momentum of flow $\rho V_1 q$ and the Froude number of flow F_1 for two spillway heights is shown in Plate 1. The following equation satisfies the data:

$$R_m = C\rho V_1 q F_1^{-P} \tag{1}$$

Values of the coefficient C were plotted versus the height of the spillway H_s (Plate 2) to obtain the following equation:

$$C = C_1 H_s^{-P_1} \tag{2}$$

Combining Equations 1 and 2 permitted development of the following equation that may be used to calculate the average minimum unit force on a sidewall

10

$$R_m = 3.75 \ H_s^{-1.05} \rho V_1 q F_1^{-1.42} \tag{3}$$

where

R_m = average minimum unit force on monolith, lb/ft

C = coefficient that is a function of spillway height

ρ = density of water, lb-sec^2/ft^4

V_1 = velocity of flow entering the stilling basin, fps

q = discharge per foot of spillway length, ft^2/sec

F_1 = Froude number of flow entering the stilling basin $V_1/\sqrt{gD_1}$ where g is the acceleration due to gravity, ft/sec^2, and D_1 is the depth of flow entering the stilling basin, ft

P = empirical exponent equal to 1.42

C_1 = coefficient equal to 3.75

P_1 = empirical exponent equal to 1.05

It should be noted that Equation 3 was derived from data involving only two spillway heights. There is a variation in the magnitude of the unit force on the monoliths throughout the length of the hydraulic jump. The length of hydraulic jump L_j , derived from Rao and Rajaratnam* is defined by:

$$L_j/D_2 = 4.9S + 6.1 \tag{4}$$

where

D_2 = theoretical sequent depth required for a hydraulic jump, ft

$S = (D_a - D_2)/D_2$, where D_a = actual tailwater depth, ft

The magnitude of the unit force on the sidewall varies along the length of the hydraulic jump. Plate 3 illustrates the variation in unit force by use of a normalizing function $[(R \text{ or } R_- \text{ or } R_+) - R_m]/(R_s - R_m)$ plotted versus a distance ratio X/L_j , where:

R = average unit force on a sidewall monolith at location X when $D_a \leq D_2$, lb/ft

R_- = minimum instantaneous unit force on a sidewall monolith at location X when $D_a \leq D_2$, lb/ft

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* N. S. Govinda Rao and N. Rajaratnam. 1963 (Jan). "The Submerged Hydraulic Jump," Journal, Hydraulics Division, American Society of Civil Engineers, Vol 89, No. HY1, pp 139-162.

R_+ = maximum instantaneous unit force on a sidewall monolith at location X when $D_a < D_2$, lb/ft

X = distance from point of intersection (PI) (Figure A1) of spillway to center line of sidewall monolith, ft

R_s = static unit force on sidewall monolith due to theoretical sequent depth for a hydraulic jump, lb/ft

Plate 3 shows the variation and permits the determination of the average, minimum, and maximum unit forces along a stilling basin sidewall when the tailwater depth D_a is equal to or less than the sequent depth D_2 . If the tailwater depth is greater than the sequent depth, R , R_+ , and R_- must be adjusted by a factor, R_a , to account for the increased forces due to the difference between tailwater depth and sequent depth (Figure 6):

$$R_a = R + \frac{\gamma}{2}\left(D_a^2 - D_2^2\right) \qquad (5)$$

$$R_{a+} = R_+ + \frac{\gamma}{2}\left(D_a^2 - D_2^2\right) \qquad (6)$$

$$R_{a-} = R_- + \frac{\gamma}{2}\left(D_a^2 - D_2^2\right) \qquad (7)$$

where

R_a = average unit force on sidewall monolith at location X when D_a exceeds D_2 , lb/ft

γ = unit weight of water, pcf

R_{a+} = maximum instantaneous unit force on sidewall monolith at location X when D_a exceeds D_2 , lb/ft

R_{a-} = minimum instantaneous unit force on sidewall monolith at location X when D_a exceeds D_2 , lb/ft

This adjustment proved effective in describing the effect of tailwater changes on the sidewall forces throughout the hydraulic jump when D_a exceeds D_2 .

Moment Analysis

12. Figure 7 presents the diagram used for determining the moment arm of the dynamic forces acting normal to the sidewalls. The total moment is represented by the force reading on the upper strain gage times its distance from the floor of the stilling basin. The total force is determined by the

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Figure 6. Sidewall loading when
tailwater depth is greater than
the sequent depth
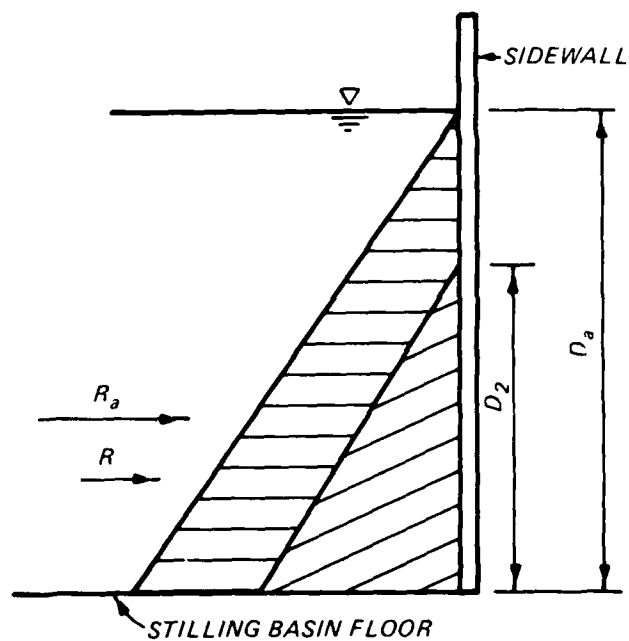
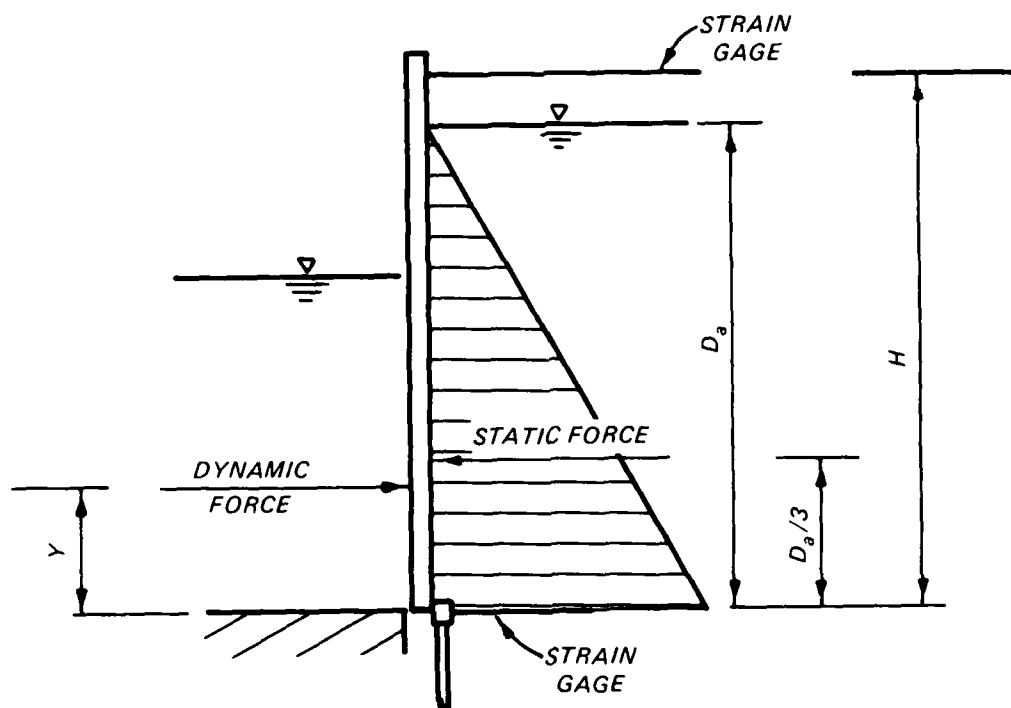$$R_a = R + \frac{\gamma}{2} \left(D_a^2 - D_2^2 \right)$$

Figure 7. Diagram for determining the moment arm of the
dynamic forces

sum of the two strain gage readings. Since the water depth D_a behind the monolith was known, it was possible to determine the resultant dynamic force and its moment arm Y (Figure A1) about the base of the monolith. Plate 4 shows the plot of Y/D_a versus the distance ratio X/L_j.
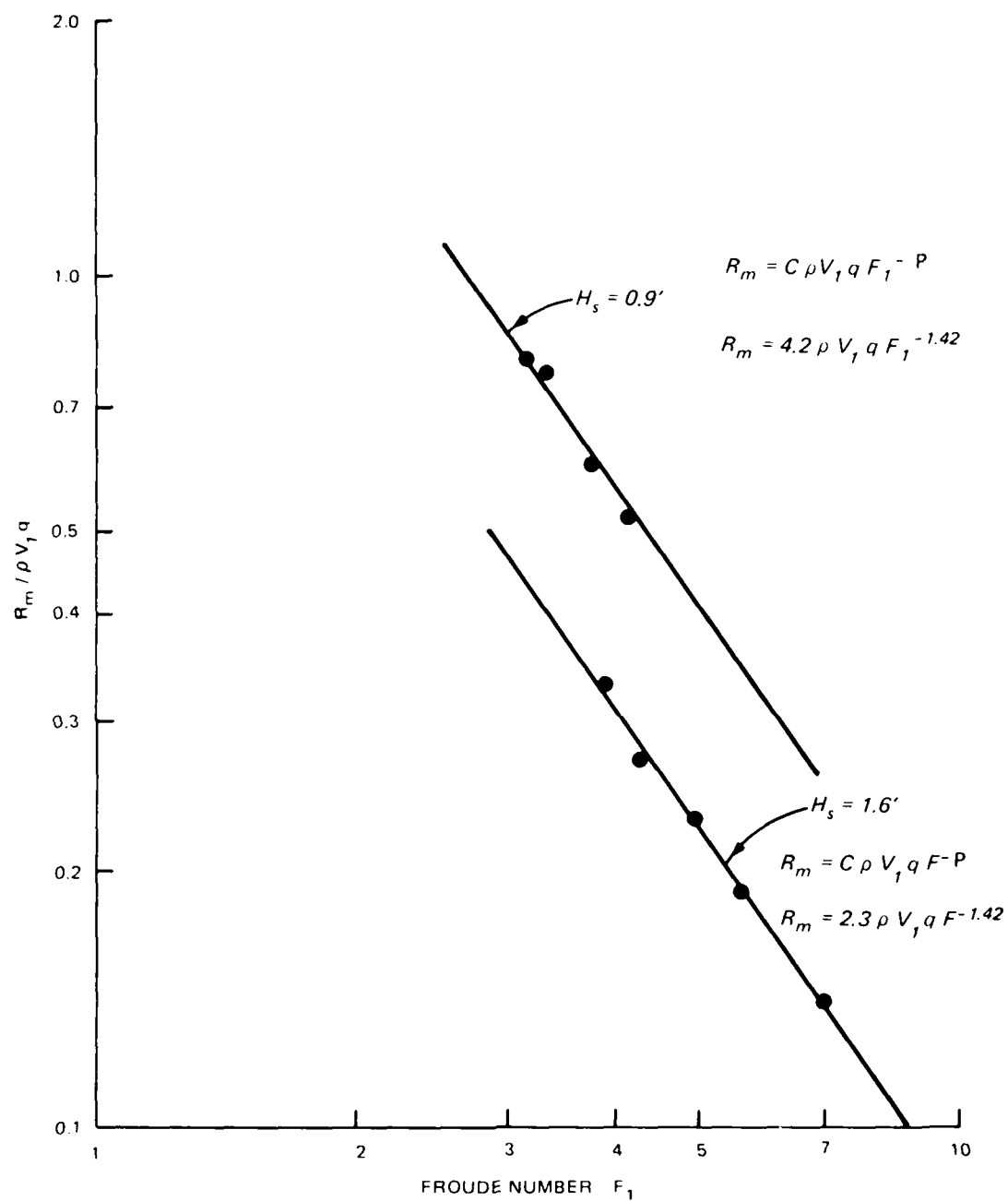
PART IV: DISCUSSION

13. These test results are limited to stilling basins without basin elements. However, it is anticipated that guidance in the design of sidewalls for stilling basins with baffles and end sill can be obtained from this report. The presence of baffles and end sill in a stilling basin would reduce the length and elevate the water-surface elevation in a hydraulic jump. A designer using the equations in this report for design of a sidewall in a stilling basin that has baffles and end sill should consider the length of the jump L_j to be equal to the stilling basin length L_b.
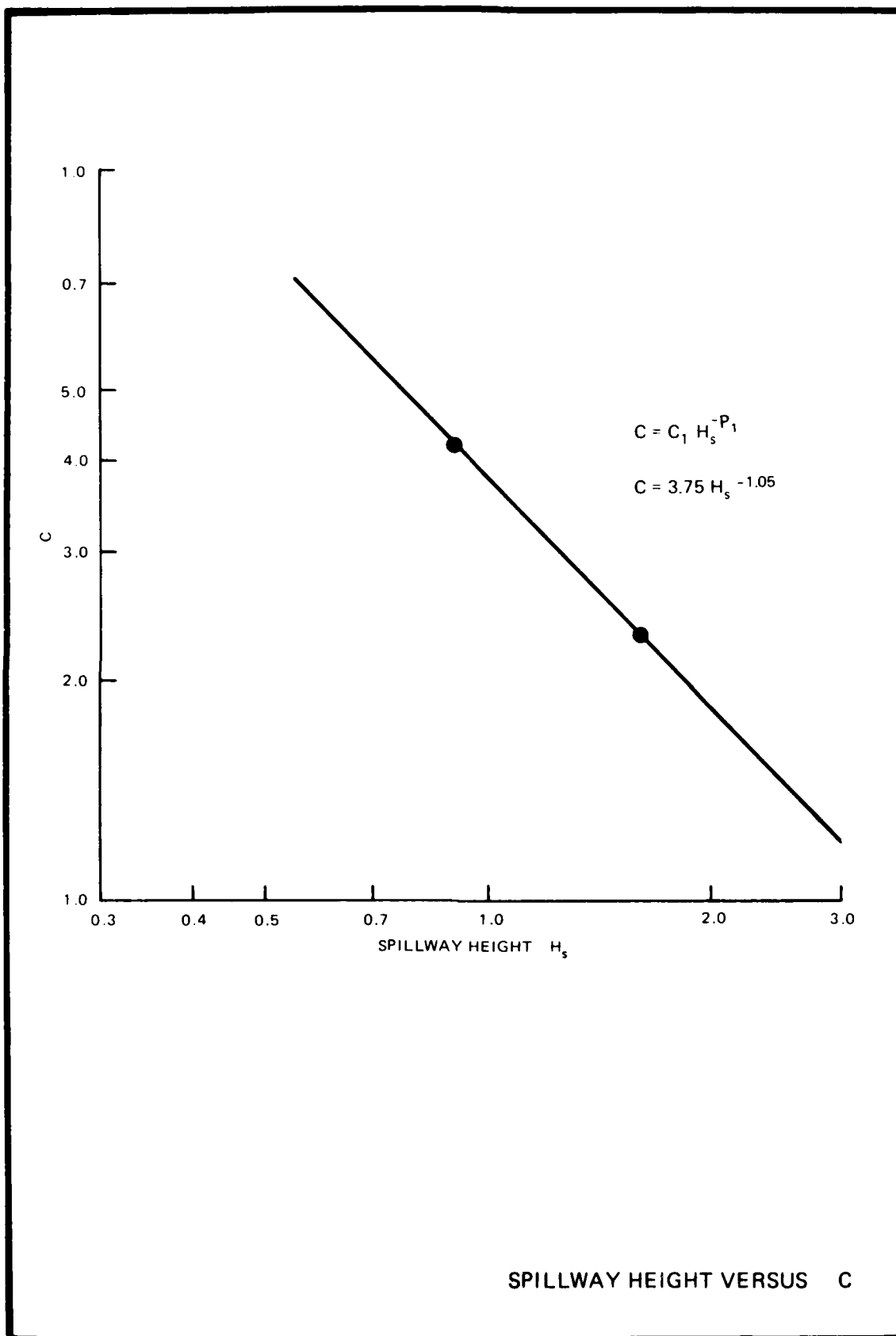
14. The average hydraulic force exerted on a sidewall is approximately equal to the static force due to the water depth in the basin, and the minimum average force occurs at a point located 15 percent of the jump length downstream from the toe of the hydraulic jump. The average minimum force can be obtained from the following equation:

$$R_m = 3.75 \ H_s^{-1.05} \rho V_1 q F_1^{-1.42} \qquad \text{(3 bis)}$$

A designer knowing the average minimum force, unit discharge, spillway height, entering velocity and Froude number, sequent depth, tailwater depth, and hydraulic jump length can compute the average force and maximum pulsations for any increment of sidewall length. Also, the maximum overturning moment about the base of any portion of the sidewall can be determined. The maximum pulsations will occur at a random frequency. Appendix A presents an example of the recommended application of the results of this study.

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$$R_m = C \rho V_1 q F_1^{-P}$$

$$R_m = 4.2 \rho V_1 q F_1^{-1.42}$$

$H_s = 0.9'$

$H_s = 1.6'$

$$R_m = C \rho V_1 q F^{-P}$$

$$R_m = 2.3 \rho V_1 q F^{-1.42}$$

2.0

1.0

0.7

0.5

0.4

0.3

0.2

0.1

$R_m / \rho V_1 q$

1　2　3　4　5　7　10

FROUDE NUMBER　F_1

FORCE VERSUS FROUDE NUMBER

PLATE 1

SPILLWAY HEIGHT VERSUS C

PLATE 2

VARIATION IN UNIT RESULTANT FORCE
WITH DISTANCE FROM PI

PLATE 3
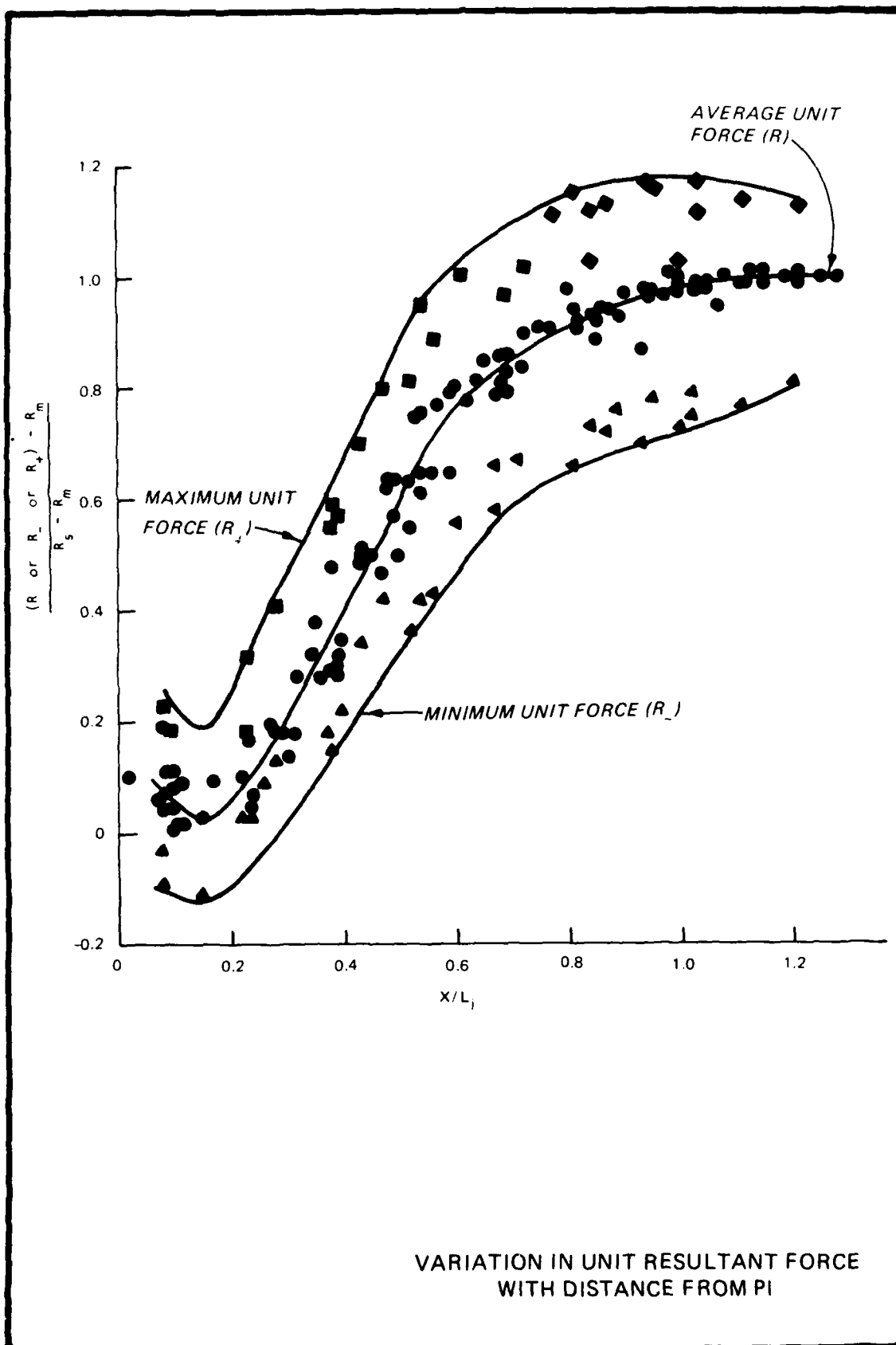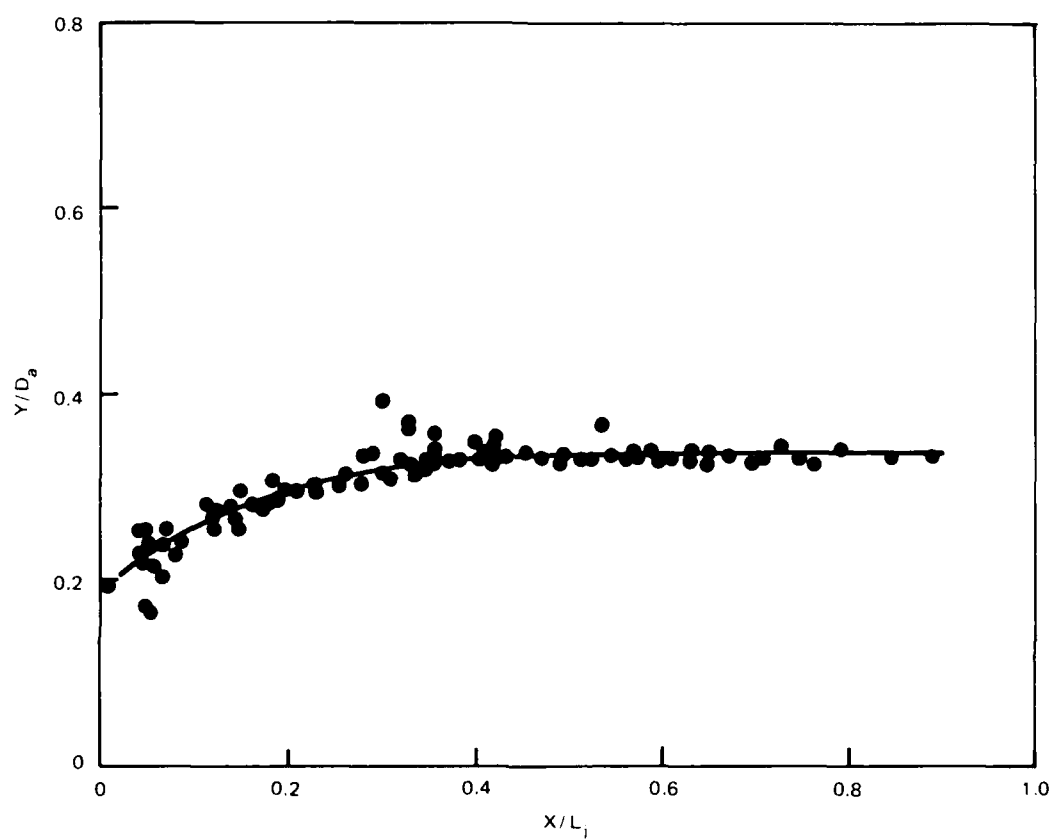
VARIATION IN MOMENT ARM WITH
DISTANCE FROM PI

PLATE 4

APPENDIX A: EXAMPLE APPLICATION

An example problem illustrating the recommended application for estimating the magnitudes and locations of the resultant dynamic forces acting on a stilling basin sidewall is presented. The results of this example problem have been adjusted, based on engineering judgment, to include the effects of the baffles and end sill.

Given (see Figure A1):

Discharge = 165,000 cfs

Pool el = 452.3*

Tailwater el = 404.0

Basin width = 240.0 ft

Crest el = 416.2

Find:

The minimum, average, and maximum hydraulic forces and the maximum moment acting on a 1-ft-wide vertical section of stilling basin sidewall 50 ft downstream from the intersection of the downstream spillway slope and the basin apron (PI).

Solution:

Determine unit discharge q , velocity V_1 , depth D_1 , and Froude number F_1 of flow entering the stilling basin:

$$q = \frac{165,000}{240} = 687.5 \text{ ft}^2/\text{sec}$$ Assume 10 percent head loss on spillway.

$$H_e = H_t - 0.1H_t$$

where H_t is the difference in elevation between pool and stilling basin apron in feet.

$$H_e = 91.3 - 0.1(91.3) = 82.2 \text{ ft}$$

$$D_1 = H_e - V_1^2/2g$$

---

* All elevations (el) cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

A1

EL 452.3 0.1 H_t

EL 416.2

H_t H_v H_s

TOP OF WALL EL 404

EL 361 y

P_i 158'

x

H_t = 91.3 FT

H_s = 55.2 FT

H_v = 82.2 FT
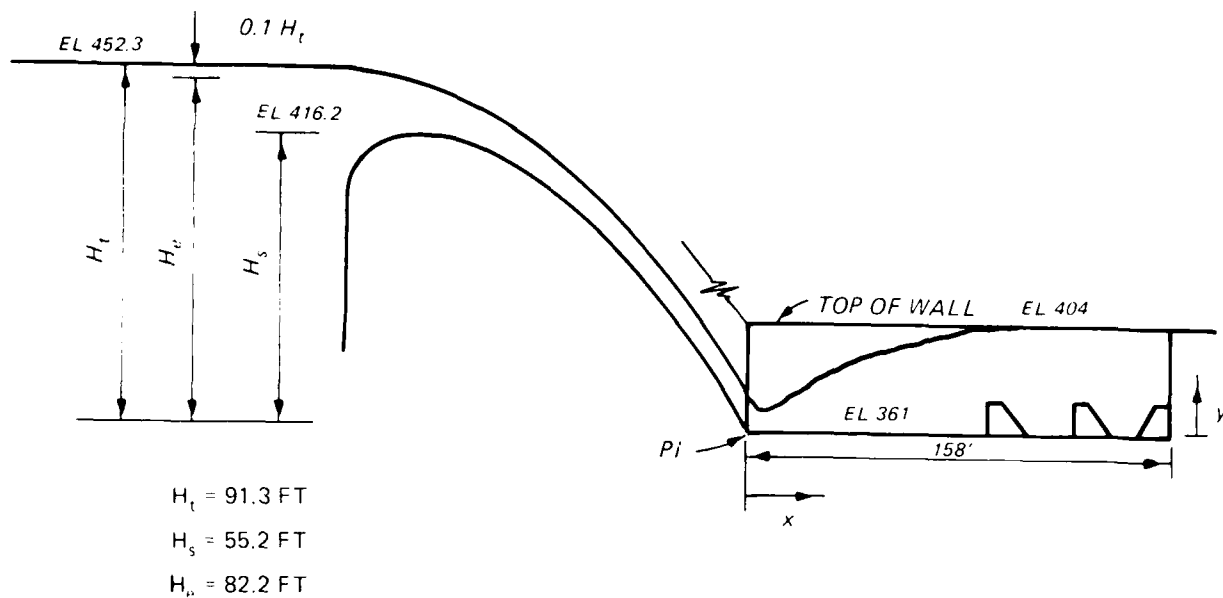
Figure A1. Example application (see notation for definition of terms)

where g is the acceleration due to gravity, ft/sec^2.

$$D_1 = 10.1 \text{ ft}$$

$$V_1 = \frac{q}{D_1}$$

$$V_1 = 68.1 \text{ fps}$$

$$F_1 = \frac{68.1}{\sqrt{32.2 \times 10.1}} = 3.8$$

$$D_a = 404 - 361 = 43 \text{ ft}$$

where D_a is the actual tailwater depth.

Determine average minimum unit force:

$$R_m = 3.75 \ H_s^{-1.05} \rho V_1 q F_1^{-1.42}$$

A2

$$R_m = 3.75(55.2)^{-1.05}(1.94)(68.1)(687.5)(3.8)^{-1.42} = 0.8 \text{ kips/ft}$$

Determine the theoretical sequent depth D_2 required for a hydraulic jump:

$$D_2 = -\frac{D_1}{2} + \sqrt{\frac{2V_1^2 D_1}{g} + \frac{(V_1)^2}{4}}$$

$$D_2 = \frac{9.4}{2} + \sqrt{\frac{2(68.1)^2 9.4}{32.2} + \frac{(10.1)^2}{4}}$$

$$D_2 = 49.5 \text{ ft}$$

Determine static unit force due to theoretical sequent depth required for a hydraulic jump:

$$R_s = \frac{\gamma D_2^2}{2} = \frac{(62.4)(49.3)^2}{2} = 76.4 \text{ kips/ft}$$

where γ is the unit weight of water, pcf.

Assume the hydraulic jump length L_j to equal the length of the stilling basin L_b . Basin length = 158 ft = L_b

$$\frac{X}{L_b} = \frac{50}{158} = 0.32$$

where X is the distance from PI of spillway to center line of sidewall monolith, ft.

Determine average unit force R :

$$\frac{R - R_m}{R_s - R_m} = 0.24 \qquad \text{(Plate 3)}$$

$$R = 0.24(R_s - R_m) + R_m$$

$$R = 0.24(76.4 - 0.8) + 0.8$$

$$R = 18.9 \text{ kips/ft} \longleftarrow$$

Determine minimum unit force R_- :

$$\frac{R_- - R_m}{R_s - R_m} = 0.043 \qquad \text{(Plate 3)}$$

$$R_- = 4.1 \text{ kips/ft} \longleftarrow$$

Determine maximum unit force R_+ :

$$\frac{R_+ - R_m}{R_s - R_m} = 0.51 \qquad \text{(Plate 3)}$$

$$R_+ = 39.4 \text{ kips/ft} \longleftarrow$$

Determine maximum unit moment M :

$$\frac{Y}{D_a} = 0.32 \quad \text{for} \quad \frac{X}{L_b} = 0.32 \quad \text{(Plate 4)}$$

where Y is the vertical distance from base of wall to location of the resultant force, ft.

$$Y = 0.32(D_a)$$

$$Y = 0.32(43) = 13.8 \text{ ft}$$

$$M = 39.4 \times 13.8 = 544 \text{ ft-kips} \longleftarrow$$

A4

APPENDIX B: NOTATION

C Coefficient that is a function of spillway height

C_1 Coefficient equal to 3.75

D_a Actual tailwater depth, ft

D_1 Depth of flow entering the stilling basin, ft

D_2 Theoretical sequent depth required for a hydraulic jump, ft

F_1 Froude number of flow entering the stilling basin $V_1/\sqrt{gd_1}$

g Acceleration due to gravity, ft/sec^2

H Height of monolith, ft

H_d Design head, ft

H_e Difference in elevation between pool and stilling basin apron minus $0.10H_t$, ft

H_s Height of spillway, ft

H_t Difference in elevation between pool and stilling basin apron, ft

L_b Length of stilling basin, ft

L_j Length of hydraulic jump, ft

M Overturning moment, lb-ft

P Empirical exponent, 1.42

P_1 Empirical exponent, 1.05

PI   Point of intersection

q Unit discharge per foot of spillway length, ft^2/sec

R Average unit force on a sidewall monolith at location X when $D_a \leq D_2$, lb/ft

R_a Average unit force on a sidewall monolith at location X when D_a exceeds D_2, lb/ft

R_m Average minimum unit force on sidewall monolith at toe of the hydraulic jump, lb/ft

R_s Static unit force on sidewall monolith due to theoretical sequent depth for a hydraulic jump, lb/ft

R_+ Maximum instantaneous unit force on sidewall monolith at location X when $D_a \leq D_2$, lb/ft

R_- Minimum instantaneous unit force on sidewall monolith at location X when $D_a \leq D_2$, lb/ft

R_{a+} Maximum instantaneous unit force on sidewall monolith at location X when D_a exceeds D_2, lb/ft

R_{a-} Minimum instantaneous unit force on sidewall monolith at location X when D_a exceeds D_2, lb/ft

S $(D_a - D_2)/D_2$

V_1 Velocity of flow entering the stilling basin, fps

X Distance from point of intersection of spillway to center line of sidewall monolith, ft

Y Vertical distance from base of wall to location of the resultant force, ft

ρ Density of water, $\mathrm{lb\text{-}sec}^2/\mathrm{ft}^4$

γ Unit weight of water, pcf

END DATED FILM

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